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Some Remarks About X-Ray Burst Sources

Walter H. G. Lewin

Department of Physics and Center for Space Research

Massachusetts Institute of Technology

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SOME REMARKS ABOUT X-RAY BURST SOURCES

Walter H. G. Lewin
Massachusetts Institute of Technology

ABSTRACT

The properties of X-ray burst sources (XRB) have recently been reviewed in great detail by Lewin and Joss (1983). Here, I will only mention some of the salient features, and I will then discuss some recent developments and some remaining problems.

INTRODUCTION

Approximately 30 XRB are known. They are distributed in a flattened distribution about the galactic center (with $|\ell| < 30^{\circ}$ and $|b| < 15^{\circ}$ for most) and are, therefore, almost certainly Population II objects (Lewin et al. 1977). This is further supported by the fact that many of the XRB are located in globular clusters (for a review see Lewin and Joss, 1981 and 1983).

By late 1976, it became clear to most workers in the field that burst sources are binary systems with an accreting neutron star. The presence of the neutron star was established in 1976-77 when the radii of burst sources were found to be near ~10 km (see, e.g., Swank et al. 1977; Hoffman, Lewin, and Doty 1977a,b; Van Paradijs 1978). Accreting neutron stars radiating at persistent levels of $\sim 10^{37}$ erg/sec require the presence of a companion star as a donor. The faintness of the optical counterparts (see, e.g., McClintock, 1977a,b; McClintock et al. 1977; Grindlay 1978) and the absence of eclipses indicated that the companion star had to be of low-mass (Milgrom 1978; Joss and Rappaport 1979). The low-mass companions were directly observed spectroscopically when the transient burst sources Aql X-1 and Cen X-4 were in their quiescent state; their masses (of the companions) were ~0.7 $M_{\odot}$ (Thorstensen, Charles, and Bowyer 1978; Van Paradijs et al. 1980). Binary periodicities have been observed in the persistent X-ray emission of two XRB: 4U 1916-05 (Walter et al. 1982, White and Swank 1982) and MXB 1659-29 (Cominsky and Wood 1983, 1984; Cominsky, this workshop.) This independently confirmed the low-mass character of these close-binary sources as did the mass estimate of X-ray sources in globular clusters (Grindlay et al. 1984).

Typical type I X-ray bursts (Hoffman, Marshall, and Lewin 1978) are detected as an order of magnitude increase in the persistent X-ray flux. Typical burst rise times are $\lesssim$ 1 sec followed by a decay which is strongly energy dependent (e.g., it could be only a few seconds at energies above 15 keV but $\sim 10^{2}$ sec at energies below 3 keV). The X-ray spectrum during the burst rise is difficult to analyze (the spectrum changes very fast), but the decay portion of the burst light curves are easy to analyze and are reasonably well represented by blackbody radiation with the observed color temperature decreasing in time.

Type II bursts from at least one source, the Rapid Burster (=MXB 1730-335) (Lewin et al. 1976a) are distinctly different. They are characterized by short recurrent times and the lack of significant spectral softening in their decaying portion (Hoffman, Marshall, and Lewin 1978).

We have a good qualitative understanding of the nature of the X-ray burst mechanisms. Type I bursts, with their cooling "tails" in the light curve, are very likely due to thermonuclear flashes in the accreted material on the surface of a neutron star (see, e.g., Woosley and Taam 1976; Maraschi and Cavaliere 1977; Joss 1978; Taam and Picklum 1979; Ayasli and Joss 1982).

Type II bursts, notably from the "Rapid Burster" (MXB 1730-335) cannot be thermonuclear in origin. The time between bursts is inadequate to allow the accretion of a "fresh" critical mass. It is thought (Lewin et al. 1976a) that such bursts are energized by spasmodic accretion related to an accretion instability (Henriksen 1976; Svestka 1976; Baan 1977, 1979; Lamb et al. 1977; Liang 1977; Michel 1977; Wheeler 1977; Horiuchi et al. 1981) perhaps similar to those occurring in dwarf novae, although with a vastly shorter time scale (Brecher, Morrison, and Sadun 1977). The burst intervals are strongly correlated with the energy in the preceding burst. The burst duration can vary from a few seconds to ~10 minutes (Lewin et al. 1976a; Marshall et al. 1979; Marshall, F. 1979; Inoue et al. 1980; Basinska et al. 1980). Sound theoretical models that explain the peculiar bursting modes are lacking. The bursting activity of the Rapid Burster also undergoes variations that appear to be cyclic. Burst activity lasts for only a few (at most ~6) weeks; it then ceases for a period of months, then starts again ~6 months later (Grindlay and Gursky 1977; Lewin 1977; Marshall et al. 1979). It is not clear that it is burst active every ~6 months (Oda, private communication; Tanaka, 1983).

PHOTOSPHERIC EXPANSION

Only very recently, it has become clear that "fast transients" with short precursors, of the kind first reported by Hoffman et al. (1978), are type I bursts of high fluence. It has been proposed by Tawara et al. (1983) and independently by Lewin, Vacca, and Basinska (1983) that the burst profiles result from an expansion and subsequent contraction of the neutron star's photosphere.

For a near constant luminosity early on in the burst, $R^2T^4_{eff}$ remains approximately constant. Here, R and T_{eff} are the photospheric radius and effective temperature. Thus an increasing (decreasing) photospheric radius will be associated with a decreasing (increasing) effective temperature. When the burst occurs, the precursor rises, the photosphere expands (Wallace, Woosley, and Weaver 1980, 1982; Taam 1982; Hanawa and Sugimoto 1982; Paczynski 1983; Ebisuzaki, Hanawa, and Sugimoto 1983; and

Kato 1983), and consequently the observed effective temperature drops, causing the precursor to decay. Spectral softening during decay of the precursor is expected and is observed. The increase in photospheric radius is large, and the effective temperature becomes so low that X rays are no longer emitted. The radius expansion occurs on a timescale of only a few seconds; this is a few orders of magnitude longer than the dynamic timescale which is puzzling. As the rate of mass outflow declines, the photospheric radius shrinks and the temperature increases. When the temperature becomes high enough, X rays will again be emitted, first at low energies and subsequently, as the temperature continues to rise, at higher energies. This explains the observed spectral hardening during the rise following the brief quiescent period after the precursor. The radius decrease stops when the photosphere has shrunk to approximately its original value and the temperature reaches a maximum. Subsequently, the neutron star's surface cools, but the photospheric radius remains nearly constant. We note that this scenario has similarities with the behavior of classical novae (Bath and Shaviv 1976; Gallagher and Starrfield 1978, and references therein).

Bursts with precursors are related to the "double-peaked" bursts which are occasionally observed at high-energy X rays (Lewin *et al.* 1976b; Hoffman, Cominsky, and Lewin 1980; Grindlay *et al.* 1980; Matsuoka 1980); they are also believed to be the result of photospheric expansion. In the double-peaked bursts, the photospheric expansion is not large enough and thus the temperature does not become low enough that the X radiation ceases. If the expansion had been much larger, the first of the two peaks would have become a precursor.

MASS AND RADIUS OF THE NEUTRON STAR

The day may come that line features are discovered in the spectra of bursts. Dr. M. Oda already made a preliminary report during this workshop on such findings from observations with Tenma.

It has been pointed out by Lewin, Vacca, and Basinska (1983) and Basinska *et al.* (1984) that the spectral lines in combination with photospheric radius variations may, in principle, allow for the determination of the neutron star's mass and radius without any knowledge of its distance. The gravitational redshift (and the Doppler shift) of the radiation from the expanding and contracting photosphere are changing throughout the burst. If spectral features (lines or absorption edges) are present in the spectra of bursts, their energies would change with time. The energy, E_∞ of the spectral features (observed by a distant observer) is related to the laboratory energy, E_o, as follows:

$$E_\infty = \frac{E_o}{1+z} \left(\frac{1+\beta}{1-\beta}\right)^{1/2}$$

where $$1 + z = \left(1 - \frac{2GM}{R_o c^2}\right)^{-1/2}$$

Here, $\beta = v/c$ (v is the radial velocity of the stellar wind as observed locally; β is always positive even if the photosphere is contracting since the stellar wind is moving radially outwards), M is the mass of the neutron star and R_o is the coordinated radius: the square root of (the locally measured surface area/4π). Measurements of E_∞ as a function of time would result in the determination of gravitational redshifts z (as a function of time) if sufficient information on β (which is also time variable) were available (the knowledge of the time variability of β may turn out to be the most difficult problem). From the data one can calculate R_∞ (which is the radius observed at large distances) as a function of time once more accurate theoretical work becomes available on the shape (color temperature versus effective temperature) of the observed spectra. The value of z(t) combined with $R_\infty(t)$ leads immediately to both R_o and the mass M of the neutron star (Van Paradijs 1979) independent of any knowledge of the distance to the system. Accurate spectral observations combined with further theoretical work, could therefore be invaluable.

IS THERE A TRUE STANDARD CANDLE ?

Van Pardijs (1978) introduced the idea that average bursts at their maximum are "standard candles" and from this he derived important and correct conclusions. He knew very well that there is a spread in the maximum burst fluxes from a given source; however, that was not essential for his objectives which were to derive approximate radii for the neutron stars and approximate source distances (see also Van Paradijs 1979, Cominsky 1981, and Lewin 1982).

Lewin (1982) suggested that the largest bursts observed from a given source are perhaps better standard candles than the average bursts (see also Cominsky 1981). It has recently been suggested by Basinska et al. (1984) that those bursts which cause a clear radius increase reach a "critical luminosity" (probably several times that of the Eddington Limit). This idea evolved from a careful study of the maximum burst fluxes of 96 bursts observed from MXB 1728-34. (See Figure 2 of Basinska et al. 1984). It may well be that this "critical luminosity" of $\sim 1.0 \times 10^{39}$ $(D/10)^2$ ergs/sec (where D is the distance in kpc to MXB 1728-34) is a "true standard candle". If that turns out to be the case, relative distances can, in principle, be accurately determined to those burst sources which produce bursts which cause clear radii increases (Hoffman, Cominsky, and Lewin 1980, Grindlay et al. 1980; Matsuoka 1980; Ohashi et al. 1982; Tawara et al. 1983; Lewin, Vacca, and Basinska 1983). Once an accurate distance is known to one of them (the globular cluster X-ray sources are the best candidates), the other distances follow and so does the value of the "true standard candle" itself. If, independently, the "true standard candle" could be calculated reliably (on theoretical grounds), the distances would follow.

MORE ON RADII OF NEUTRON STARS - BLACKBODY SPECTRA - EFFECTIVE AND COLOR TEMPERATURES

The radii of neutron stars are calculated from the observed blackbody spectra. The calculated values for the radii are on the average near ~7 km (Van Paradijs 1978, 1979; Comminsky 1981). This is below the lowest possible value of 10.74 km that can be observed for the radius of any 1.4 $M_\odot$ object (Van Paradijs 1979; Paczynski 1983). Recent developments may, at least in principle, have resolved this apparent discrepancy.

For an approximate blackbody spectrum, it is expected that the color temperature (derived from the X-ray spectra) is higher than the effective temperature (Van Paradijs 1982; Czerny and Sztajno 1983). In calculating neutron star radii, the color temperatures were always used, and thus all reported radii are too low. As an example, I find in the paper by Czerny and Sztajno (1983) that (for an object with log g = 14, which is typical for neutron stars) the effective temperature (kT) is ~ 1.65 keV when the observed color temperature is ~2.5 keV (typical value at burst maximum). This would increase the radii at burst maximum by a factor ~ $(2.5/1.65)^2$ ~ 2.3, and this would bring the observed values comfortably above the lowest possible value (of 10.74 km) that can be observed for a 1.4 $M_\odot$ object.

G-STAR IDENTIFICATIONS ???

Some bright XRB have been identified by Grindlay (1981) with G stars. Such identifications are puzzling at best. The companion star in the binary system could perhaps be a G star, but the optical spectrum in the presence of a strong X-ray flux will be dominated by X-ray heating (blue spectrum + emission lines) and is therefore very different from that of a G star. Therefore, such identifications are bound to be incorrect (for a review on optical properties, see Van Paradijs 1983).

Later, Grindlay and Hertz (1983) and Grindlay (this workshop) noted that the X-ray sources lie within a few arc sec of the G stars which makes a lot more sense. However, they believe that the X-ray sources and the G stars are associated. They propose that the burst sources observed outside globular clusters have been formed inside globular clusters that have subsequently been tidally disrupted. They argue that the observed proximity - in four of twelve cases - of a normal star and an X-ray burst source is observational evidence for their proposed scenario.

Jan van Paradijs and I have evaluated the arguments presented by Grindlay and Hertz (1983), and we have concluded that there is insufficient evidence for their scenario.

SOME REMAINING PROBLEMS

- The formation of low-mass X-ray binaries outside globular clusters remains a major puzzle (see Van den Heuvel, 1983).
- It is still unclear why bursts at their maximum can radiate at a level substantially above the Eddington limit.
- In the context of the present thermonuclear flash models, it is unclear why type I bursts can occur at very short intervals of ~ 5-10 minutes (for a review, see Lewin and Joss 1983).
- It is not clear yet why burst intervals from one source can vary by an order of magnitude and more without an appreciable change in the observed persistent X-ray flux.
- It is unclear why the expansion timescale of the photospheric radius of the neutron star (in the case of very strong bursts) can be a few seconds (this is about three orders of magnitude longer than the dynamic time scale).
- No sound models exist to date that can explain the peculiar bursting behavior of the type II bursts from the Rapid Burster.

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